Investigations of Rheological Properties of Asphalt Binders Modified with Scrap Polyethylene

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# Table of Content

Introduction ........................................................................................................................................... 3
Material and Methods ................................................................................................................................. 4
  Materials and Experimental Design ......................................................................................................... 4
  Brookfield rotational viscosity test ........................................................................................................ 5
  Performance grade (PG) determination .................................................................................................... 6
  Multi-stress creep recovery (MSCR) test .................................................................................................. 6
  Linear amplitude sweep (LAS) test .......................................................................................................... 6
  Frequency sweep and amplitude sweep test .......................................................................................... 6
Results and Discussions .............................................................................................................................. 7
  Unaged binders ......................................................................................................................................... 7
    Rotational viscosity ............................................................................................................................... 7
    Failure temperature .............................................................................................................................. 8
    $G \times \sin\delta$ .................................................................................................................................... 9
    Frequency sweep ................................................................................................................................. 11
    Amplitude sweep ................................................................................................................................. 13
  RTFO-aged binders ................................................................................................................................. 16
    Failure temperature .............................................................................................................................. 16
    $G \times \sin\delta$ .................................................................................................................................... 17
    Frequency sweep ................................................................................................................................. 20
    Amplitude sweep ................................................................................................................................. 22
    Temperature sweep .............................................................................................................................. 24
    MSCR .................................................................................................................................................. 26
  PAV-aged binders .................................................................................................................................... 29
    Low temperature properties .................................................................................................................. 29
    Fatigue property .................................................................................................................................... 33
Conclusions .................................................................................................................................................. 36
References .................................................................................................................................................... 38
Appendix A .................................................................................................................................................. 39
  Rotational viscosity ............................................................................................................................... 39
    $G \times \sin\delta$ .................................................................................................................................... 40
  Stiffness and $m$-value ............................................................................................................................ 49
Introduction

Nowadays, environmental sustainability has become the main issue in many projects around the country and the world. Particularly, the problem of where and how to dispose the large amount of the daily waste is one of the concerns of many municipalities all over the world (1).

Waste plastic is a material composed by one or more types of high-molecular organic polymers, which is solid in general state and can flow under specific state (2). There are many types of waste plastics, including polyethylene (PE), polypropylene (PP), polystyrene (PS) and so on. Meanwhile, the disposal of waste plastic is also an issue of great concern worldwide due to its considerable quantity and growth. In order to handle this problem, many recycling techniques and research studies about the incorporation of waste plastic into asphalt binders and mixtures have been conducted (3). And among all types of waste plastic used in paving applications, PE has a prominent utilization.

Hinislioglua et. al (4) studied the feasibility of modified binders using various waste plastics containing high density polyethylene (HDPE) in different content and used them in an asphalt mixture. Binders used in hot mix asphalt (HMA) were made by mixing the HDPE in 4, 6 and 8 % (by weight of optimum asphalt content) and base binder AC-20 at 145, 155 or 165 °C and mixed for 5, 15 or 30 minutes. They concluded that the asphalt mixture with 4 % HDPE, which was mixed at 165 °C for 30 min, showed the highest stability and the smallest flow value. Moreover, the mixture was also greatly resistant to rutting. Therefore, they concluded that these types of mixtures could be utilized to make an asphalt pavement which has more resistance to permanent deformation while solving a problem with the waste plastic disposal. Attaelmanan et al. (5) investigated the possibility of using PE as a modifier for asphalt. They modified the 80/100 penetration grade asphalt by adding different contents of PEs (by weight of asphalt). The standard asphalt binder tests indicated that the softening point increased, and the penetration and temperature susceptibility decreased as the PE content increased. The results also indicated that the performances of PE modified asphalt mixtures were better than traditional mixtures, with greater stability, tensile strength ratios and resilient modulus values. Hence, they reported that flexible pavements with higher performance and durability and lower costs than conventional pavements could be obtained with an additional 5 % PE.

Fuentes-Aude´n et al. (3) carried out a study about the impacts of polymer content on the recycled PE modified asphalt. The base binder was a 150/200 penetration grade asphalt. To analyze the evolution mechanism of micro-conducted including optical microscopy, modulated differential scanning calorimetry (MDSC) measurements, steady and oscillatory shear tests and dynamic mechanical thermal analysis (DMTA); respectively, were utilized. The results indicated that the addition of PE to asphalt produced a significant improvement to some of mechanical properties, such as higher resistance to permanent deformation, thermal cracking and fatigue cracking. They further concluded that the modified binder of low PE content (less than 5 %) could be possibly applied to highway pavements.
However, even though it was found that adding PE could minimize the thermal cracking (6), the low temperature performance of asphalt could not be improved by adding PE alone (7). Therefore, PE seemed to be less effective in low temperature property specially compared with crumb rubber (CR) and styrene-butadiene-styrene (SBS).

Many researchers have indicated that the utilization of PE in asphalt reduces the volume of waste, conserve both material and energy and provides a comparatively simple way to make a substantial reduction in the overall volume of solid waste. Furthermore, PE could enhance some rheological characteristics of asphalt binders and better performing field mixtures. On the other hand, the key challenge of PE modified binder lied in its poor low temperature performance.

Material and Methods
Materials and Experimental Design
Two base binders of different sources (PG 64-22 binder) were used to produce polyethylene (PE) modified binders, referred to as binder A and B, at a blending temperature of 350F (177C) and mixing for 2 hours (700 rpm). Three types of PE were utilized, and the designed three PE contents included 2%, 4% and 6% by weight of base binder. The base binders were also blended for 2 hours at 350F to avoid the temperature impact. In addition, two styrene-butadiene-styrene (SBS) modified binders (PG 76-22) and two crumb rubber modified (CRM) binders were employed, for comparison purposes, in this study. The experimental design for this research project is shown in Figure 1. For each test, at least two replicates were prepared and tested.
In this study, three aging states of all binders were investigated, including original state, rolling thin film oven (RTFO) aging state (short-term aging) and pressured aging oven (PAV) state (long-term aging). In addition, the following tests were performed according to AASHTO or ASTM specifications.

**Brookfield rotational viscosity test**

Brookfield rotational viscometer was used to test the viscosity of the unaged binders at three different temperatures (e.g. 135 °C, 150 °C, and 165 °C) in
accordance with AASHTO T316. A number 27 spindle and a specimen weight of 8-11 g was used for this test.

**Performance grade (PG) determination**

Dynamic shear rheometer (DSR) was used to measure the intermediate and high temperature rheological properties of binders based on AASHTO T315. The complex shear modulus ($G^*$) and phase angle ($\delta$) values were measured at the given temperature. According to AASHTO M320, a bending beam rheometer (BBR) was used to test the PG low temperature grade by using the PAV-aged binders.

**Multi-stress creep recovery (MSCR) test**

The MSCR test was conducted by the repeated loading for duration of 1 s followed by 9 s of recovery period using the DSR system in accordance with ASTM D7405-15. All RTFO-aged binders were tested at 76 °C and a 15-min temperature equilibrium period was used before the initiation of the test procedure. Two stress levels of 0.1 kPa and 3.2 kPa were applied and 10 cycles were conducted for each stress level. The MSCR test uses two parameters, the percent recovery ($R$) and the non-recoverable creep compliance ($J_{nr}$), to characterize the viscoelasticity properties of an asphalt binder. Two parameters are calculated as the following two equations:

\[ R = \frac{\text{SUM}((\varepsilon_1 - \varepsilon_{10})/\varepsilon_1)}{10} \]  
\[ J_{nr} = \frac{\text{SUM}(\varepsilon_{10}/\tau)}{10} \]  

Where: $\varepsilon_1$ is the strain at the first second for each cycle, $\varepsilon_{10}$ is the strain at the tenth second for each cycle, and $\tau$ is the applied shear stress level.

**Linear amplitude sweep (LAS) test**

According to AASHTO TP 101-12, the LAS test was used to evaluate the fatigue resistance of binders by applying cyclic load with increasing amplitude. And it was conducted using DSR with a 2 mm working gap and an 8 mm diameter plate at 25°C. Meanwhile, each binder sample was further aged using RTFO and PAV to simulate the short and long-term aging procedures of asphalt pavements. Based on the viscoelastic continuum damage (VECD) theory, the test results, i.e. the fatigue life ($N_f$) of binders, can be calculated by Eq. (3) below. The failure of binders is defined as 35% decrease in initial modulus.

\[ N_f = A_{35} (\gamma_{max})^{-B} \]  

Where: $N_f$ is failure life, $\gamma_{max}$ is the maximum shear strain for the given pavement structure, finally $A_{35}$ and $B$ are the parameters which depend on the material characteristics.

**Frequency sweep and amplitude sweep test**

The amplitude sweep, and frequency sweep test were carried out at 64 °C for each base binder and at 76 °C for modified binders. Amplitude sweep tests were measured at varying shear stresses and strains. For the frequency sweep tests, frequency ranged from 0.1 to 100 Hz were selected to run at 0.1 kPa.
Results and Discussions
Unaged binders
Rotational viscosity

The rotational viscosity is used to determine the flow characteristics of an asphalt binder and to make sure that it can be pumped and handled at the asphalt plant. In this report, the viscosity values of each binder were obtained at 135 °C, 150 °C and 165 °C, and, as expected, the viscosity of all asphalt binders decreased as the test temperature increased. The viscosity values of various binders from two sources at 135 °C are shown in Fig. 2. In addition, the viscosity values at 150 °C and 165 °C are presented in appendix A.

![Fig. 2 Rotational viscosity results of two binder sources](image-url)
Fig. 2 indicated that PE modified asphalts generally showed higher viscosity than those base binders, CRM binders and SBS modified binders. The viscosity value increases with an increase in the amount of PE additives regardless of the binder type. On the other hand, it seemed that there was no significant relationship between viscosity and PE type.

**Failure temperature**

The grade determination feature of the DSR was used to determine the failure temperatures of various binders. This procedure tested the sample at a starting temperature and increased the temperature to the next PG grade if the $G^*/\sin \delta$ value was greater than the value required by AASHTO M320 (1.0 kPa for original binders). Two replicates were tested for each binder, and the results are shown in Fig. 3.
As shown in Fig. 3, PE could effectively improve the failure temperature of base binders, and PE modified binders even showed higher failure temperatures when compared with those CRM and SBS binders. Obviously, the failure temperature of PE modified asphalt increased with PE content from 2% to 6%. And for binder A, binders modified by PE3 tended to have the highest failure temperature, followed by PE1 and PE2. While for binder B, the rank was: PE2 > PE1 > PE3.

\( G^*/\sin \delta \)

Based on the values of complex modulus \( (G^*) \) and phase angle \( (\delta) \), the values of rutting resistance factor \( (G^*/\sin \delta) \) at the performance test temperatures of each original binder are shown in Fig. 4. Other related data are presented in the appendix A.
(a) Binder A with varying PE contents (PE type: PE2)

(b) Binder A with varying PE types (PE content: 4%)
As shown in Fig. 4, the $G^*/\sin \delta$ value shows similar trends to failure temperature. The binders with higher PE content tented to have higher $G^*/\sin \delta$ values. And that which type of PE modified binder performed the highest $G^*/\sin \delta$ value depended on the base binder source and test temperature.

**Frequency sweep**

The frequency sweep tests were performed under stress proportional to frequency, and the used frequencies were from 0.1 to 100 Hz in this research project. The
frequency sweep tests at various frequencies could identify the linear viscoelastic response of the binders. The test results are shown in Fig. 5.

(a) Complex modulus versus frequency (Binder A)

(b) Phase angle versus frequency (Binder A)
As shown in Fig. 5, it could be found that the increased frequency generally resulted in an increase of complex modulus for all asphalt regardless of the binder source. In terms of phase angle, the phase angle of the binder with highest PE content (6%) truly increased at first and then decreased with the increased frequency. For binder with PE contents of 2% and 4%, increased frequency always resulted in a decreased phase angle. Moreover, it could be observed that with the increased dosage of PE, the complex modulus increased regardless of binder type, while the phase angle values decreased in most frequencies. Furthermore, this test indicated that the viscoelastic property of various binders was based on the PE content and type.

**Amplitude sweep**

In this project, the amplitude sweeps were performed to determine the complex
modulus and phase angle values in terms of the shear strain responses. The results of original binders are presented in Fig. 6.

(a) Complex modulus versus shear strain (Binder A)

(b) Phase angle versus shear strain (Binder A)
As shown in Fig. 6, the increased shear strain (from 0.1% to 1.0%) significantly reduced the complex modulus and increased the phase angle of binders with high PE contents (4% and 6%). In terms of binder source, there was only a slight change of complex modulus and phase angle for binder B with increased shear strain, while binder A tended to show a greater change than binder B. On the other hand, shear strain did not, as expected, influence these binders with PE content of 2%. In addition, with the increased amount of PE, the complex modulus increased, and phase angle decreased. Thus, additional PE not only reinforced the viscosity of binders but also enhanced the elasticity.
RTFO-aged binders

*Failure temperature*

The grade determination feature of the DSR was used to determine the failure temperature for various RTFO aged (short-term aging) binders. This procedure tested the sample at a starting temperature and increased the temperature to the next PG grade if the $G^*/\sin \delta$ value was greater than the value required by AASHTO M320 (2.2 kPa for the RTFO-aged binder). Two replicates were tested for each binder, and the failure temperature of RTFO-aged binders are shown in Fig. 7.

![Failure temperature of RTFO-aged binders](image)

**Fig. 7** Failure temperature of RTFO-aged binders
As shown in Fig. 7, PE modified binders showed higher failure temperature even when compared with those of CRM and SBS modified binders. Obviously, the failure temperature of PE modified asphalt increased with PE content between 2% and 6%. And for binder A, binders modified by PE3 tended to have the highest failure temperatures, followed by PE2 and PE1. While for binder B, the rank was: PE1 > PE2 > PE3. The high temperature grades of various binders are represented in Table 1.

<table>
<thead>
<tr>
<th>Binder type</th>
<th>High temperature grade (℃)</th>
<th>Binder type</th>
<th>High temperature grade (℃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>70</td>
<td>B</td>
<td>70</td>
</tr>
<tr>
<td>A-CRM-15%</td>
<td>82</td>
<td>B-CRM-15%</td>
<td>82</td>
</tr>
<tr>
<td>A-SBS</td>
<td>76</td>
<td>B-SBS</td>
<td>76</td>
</tr>
<tr>
<td>A-PE1-2%</td>
<td>82</td>
<td>B-PE1-2%</td>
<td>76</td>
</tr>
<tr>
<td>A-PE1-4%</td>
<td>82</td>
<td>B-PE1-4%</td>
<td>82</td>
</tr>
<tr>
<td>A-PE1-6%</td>
<td>88</td>
<td>B-PE1-6%</td>
<td>94</td>
</tr>
<tr>
<td>A-PE2-2%</td>
<td>76</td>
<td>B-PE2-2%</td>
<td>82</td>
</tr>
<tr>
<td>A-PE2-4%</td>
<td>82</td>
<td>B-PE2-4%</td>
<td>88</td>
</tr>
<tr>
<td>A-PE2-6%</td>
<td>94</td>
<td>B-PE2-6%</td>
<td>88</td>
</tr>
<tr>
<td>A-PE3-2%</td>
<td>82</td>
<td>B-PE3-2%</td>
<td>76</td>
</tr>
<tr>
<td>A-PE3-4%</td>
<td>88</td>
<td>B-PE3-4%</td>
<td>82</td>
</tr>
<tr>
<td>A-PE3-6%</td>
<td>94</td>
<td>B-PE3-6%</td>
<td>88</td>
</tr>
</tbody>
</table>

\( G^*/\sin \delta \)

Based on the values of complex modulus \( (G^*) \) and phase angle \( (\delta) \), the values of rutting resistance factor \( (G^*/\sin \delta) \) at the performance test temperatures of each RTFO-aged binder are shown in Fig. 8. In addition, other data are presented in the appendix A.
(a) Binder A with varying PE contents (PE type: PE2)

(b) Binder A with varying PE types (PE content: 4%)
As shown in Fig. 8, the $G^* / \sin \delta$ values show similar trends to failure temperature. The binders with higher PE content tended to have higher $G^* / \sin \delta$ values. The base binder source, test temperature and aged state affected the performance of the PE modified binder regarding the $G^* / \sin \delta$ value.
**Frequency sweep**

The frequency sweep tests were performed under stress proportional to frequency, and the used frequencies were from 0.1 to 100 Hz in this research. The frequency sweep tests at various frequencies could identify the linear viscoelastic response of binders. The test results of RTFO-aged binders are shown in Fig. 9.

(a) Complex modulus versus frequency (Binder A)

(b) Phase angle versus frequency (Binder A)
As shown in Fig. 9, it could be found that the increased frequency generally resulted in an increase of complex modulus and a reduction of phase angle regardless of binder type. As an exception, for the binder B modified by PE1 and PE 2 (including 2%, 4% and 6%), the phase angle increased firstly and decreased then with the increased frequency. Moreover, it could be observed that with the increased dosage of PE, the complex modulus increased regardless of binder type, while the phase angle values decreased in most frequencies. Therefore, it could be concluded that the frequency sweep test indicated that the viscoelastic properties of various binders were based on the PE content and type. In addition, the complex modulus values of most original binders are lower than those of RTFO-aged binders, and their phase angle values are higher than RTFO-aged binders.
**Amplitude sweep**

In this research, the amplitude sweeps were performed to determine the complex modulus and phase angle values in terms of the shear strain responses. The results of RTFO-aged binders are presented in Fig. 10.

(a) Complex modulus versus shear strain (Binder A)

(b) Phase angle versus shear strain (Binder A)
The test results in Fig. 10 illustrated that the increased shear strain significantly reduced the complex modulus and increased the phase angle of binders with high PE content (4% and 6%), regardless of the binder source. On the other hand, shear strain does not obviously influence these binders with PE content of 2%. In addition, with the increased amount of PE, the complex modulus increased, and phase angle decreased. Thus, additional PE generally not only reinforced the viscosity of binders but also enhanced the elasticity.
Temperature sweep

In this research, the temperature sweeps were performed to determine the complex modulus and phase angle values in terms of temperature responses. The results of RTFO-aged binders are presented in Fig. 11.

(a) Complex modulus versus temperature (Binder A)

(b) Phase angle versus temperature (Binder A)
The test results in Fig. 11 indicated that the increasing temperature significantly reduced the complex modulus and increased the phase angle of binders, regardless of the binder type. With the increasing PE content, the complex modulus increased, and phase angle decreased at each test temperature. In addition, PE modified binders generally showed higher complex modulus and lower phase angle values when compared to the references (including virgin, CRM and SBS binders). Thus, additional PE generally not only improved the viscosity but also enhanced the elasticity of the binders. Moreover, there was no significant correlation between the PE type and the viscoelasticity of binders.
MSCR

The MSCR tests were conducted at 76°C and the results are shown in Figs. 12 and 13. The values of non-recoverable creep compliances ($J_{nr}$) and percentage recoverable strains ($R$) under 0.1 kPa of various binders are presented in Fig. 12. In addition, the rebound curves of shear strain versus test time are shown in Fig. 13.
(c) Percentage recoverable strain ($R$) at 0.1 kPa (Binder B)

(d) Non-recoverable creep compliance ($J_{nr}$) at 0.1 kPa (Binder B)

Fig. 12 MSCR test results
As shown in Fig. 11, the elastic performance of base binder was improved by the PE modifier, as the PE modified binders showed higher $R$ and lower $J_{nr}$ values when compared to the references. In other words, these PE modified binders had better recovery performances at high temperatures. And an increased PE content resulted in a reduction of $J_{nr}$ and an increase of $R$. Furthermore, Fig. 12 identified that the binders with higher PE content showed greater recovery performances and the PE modified binder with content of 2% and 4% tended to show poorer recovery.
performance that CRM and SBS binder. Regarding PE types: for binder A, binders modified by PE3 had the best recovery performances, followed by PE1 and PE2 orderly. For binder B, the best modifier was PE1, and then PE2 and PE3, respectively. Regarding binder source, binder B modified by PE obviously showed greater recovery performance than binder A with much higher recovery percent and lower non-recoverable creep compliance.

**PAV-aged binders**

*Low temperature properties*

This project employed BBR to test asphalt beam’s deformation as a function of loading time, thus stiffness and m-value could be calculated at different temperatures (-6 °C, -12 °C and -18 °C), as shown in Fig. 14. In order to prevent thermal cracking, the creep stiffness has a maximum limit of 300 MPa, and m-value is limited to a minimum value of 0.3 at 60 s of loading time according to Superpave specification. And the PG low temperature grade was determined by these two criterions. The critical low temperatures of various binders are shown in Fig. 15. Other related data results are presented in Appendix A.

1) *Stiffness and m-value*

(a) Binder A with varying PE contents (PE type: PE2)
(b) Binder A with varying PE types (PE content: 4%)

(c) Binder B with varying PE contents (PE type: PE2)
Table 2 presented the determination of critical low temperature of all binders according to the stiffness and m-value. The results of critical low temperature were shown in Fig. 15. It was obvious that the low temperature grade of PE modified binder was controlled by the m-value.

2) **Critical low temperatures**

Table 2 **Determination of critical low temperature**

<table>
<thead>
<tr>
<th>Binder type</th>
<th>Stiffness-determined (°C)</th>
<th>m-determined (°C)</th>
<th>Critical low temperature (°C)</th>
<th>Delta Tc (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-11.8</td>
<td>-8.1</td>
<td>-8.1</td>
<td>3.7</td>
</tr>
<tr>
<td>A-CRM-15%</td>
<td>-20.1</td>
<td>-7.5</td>
<td>-7.5</td>
<td>12.6</td>
</tr>
<tr>
<td>A-SBS</td>
<td>-17.2</td>
<td>-12.3</td>
<td>-12.3</td>
<td>4.9</td>
</tr>
<tr>
<td>A-PE1-2%</td>
<td>-11.4</td>
<td>-4.6</td>
<td>-4.6</td>
<td>6.8</td>
</tr>
<tr>
<td>A-PE1-4%</td>
<td>-10.3</td>
<td>-3.3</td>
<td>-3.3</td>
<td>7.0</td>
</tr>
<tr>
<td>A-PE1-6%</td>
<td>-11.4</td>
<td>-0.9</td>
<td>-0.9</td>
<td>10.5</td>
</tr>
<tr>
<td>A-PE2-2%</td>
<td>-10.8</td>
<td>-4.2</td>
<td>-4.2</td>
<td>6.6</td>
</tr>
<tr>
<td>A-PE2-4%</td>
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<td>-1.8</td>
<td>-1.8</td>
<td>9.5</td>
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<tr>
<td>A-PE2-6%</td>
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<td>-0.3</td>
<td>-0.3</td>
<td>12.2</td>
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<tr>
<td>A-PE3-2%</td>
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<td>-2.2</td>
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<tr>
<td>A-PE3-4%</td>
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<td>-0.9</td>
<td>-0.9</td>
<td>9.1</td>
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<tr>
<td>A-PE3-6%</td>
<td>-11.0</td>
<td>-0.1</td>
<td>-0.1</td>
<td>10.9</td>
</tr>
<tr>
<td>B</td>
<td>-12.2</td>
<td>-8.1</td>
<td>-8.1</td>
<td>4.1</td>
</tr>
<tr>
<td>B-CRM-15%</td>
<td>-17.8</td>
<td>-7.1</td>
<td>-7.1</td>
<td>10.7</td>
</tr>
<tr>
<td>B-SBS</td>
<td>-14.4</td>
<td>-7.7</td>
<td>-7.7</td>
<td>6.7</td>
</tr>
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</table>
B-PE1-2%  -11.8  -5.0  -5.0  6.8  
B-PE1-4%  -11  -1.3  -1.3  9.7  
B-PE1-6%  -11.5  -1.0  -1.0  10.5  
B-PE2-2%  -10.6  -2.1  -2.1  8.5  
B-PE2-4%  -11.9  -0.7  -0.7  11.2  
B-PE2-6%  -11.3  -1.0  -1.0  10.3  
B-PE3-2%  -12.4  -2.0  -2.0  10.4  
B-PE3-4%  -11.5  -1.0  -1.0  10.5  
B-PE3-6%  -10.5  -0.3  -0.3  10.2  

Fig. 15 Critical low temperature of various binders
Fig. 15 shows that PE modified binders produced higher critical low temperature than those base binders, CRM binders and SBS binders, which means that PE had a negative effect on low temperature property of binders. And when the PE content increased, the absolute value of critical low temperature decreased. In other words, binders with higher PE content tended to have higher stiffness and lower m-value, as shown in Fig. 14. With regards to PE type, PE3 was the worst produced modifier, followed by PE2 and PE1. The low temperature grades of various binders are presented in Table 3.

<table>
<thead>
<tr>
<th>Binder type</th>
<th>Low temperature grade (°C)</th>
<th>Binder type</th>
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<td>A</td>
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<td>-16</td>
<td>B-CRM-15%</td>
<td>-16</td>
</tr>
<tr>
<td>A-SBS</td>
<td>-22</td>
<td>B-SBS</td>
<td>-16</td>
</tr>
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<td>A-PE1-2%</td>
<td>-10</td>
<td>B-PE1-2%</td>
<td>-10</td>
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<td>A-PE1-6%</td>
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<td>B-PE1-6%</td>
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<td>A-PE2-2%</td>
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</tr>
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<td>A-PE2-4%</td>
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<td>B-PE2-4%</td>
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<td>A-PE2-6%</td>
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<td>B-PE2-6%</td>
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</tr>
<tr>
<td>A-PE3-2%</td>
<td>-10</td>
<td>B-PE3-2%</td>
<td>-10</td>
</tr>
<tr>
<td>A-PE3-4%</td>
<td>-10</td>
<td>B-PE3-4%</td>
<td>-10</td>
</tr>
<tr>
<td>A-PE3-6%</td>
<td>-10</td>
<td>B-PE3-6%</td>
<td>-10</td>
</tr>
</tbody>
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**Fatigue property**

1) \(G^* \sin \delta\)

SHRP employs \(G^* \sin \delta\) (fatigue factor) to evaluate the binder fatigue resistance, which is based on linear viscoelastic properties of the binders. From viewpoint of fatigue cracking resistance, a lower \(G^* \sin \delta\) value is considered desirable. \(G^*\) and \(\delta\) of each binder were measured through PG test for PAV binder at 31 °C. The values of \(G^* \sin \delta\) are presented in Fig. 16.
Fig. 16 $G^*\sin \delta$ of PAV-aged binders

Fig. 16 shows that PE modified binders produced higher $G^*\sin \delta$ values when compared to other references, which revealed that the PE modifier had a negative effect on the fatigue resistance performance regardless of the base binder sources. Moreover, it was found that the higher PE content, the poorer fatigue resistance. In addition, with regards to PE type, the worst produced modifier was PE3, followed by PE2 and PE1, respectively.
2) LAS

The LAS test can obtain considerable data in 30 min and produces a good correlation with the filed fatigue cracking data. The fatigue life of each binder could be calculated. Fig. 17 presents the relationship between fatigue life (\(N_f\)) and the applied shear strain.

In contrast to the results of fatigue factor (\(G^* \sin \delta\)), Fig. 17 indicated that PE modified binder showed longer fatigue life, i.e. higher fatigue cracking resistance, than base binders regardless of the PE type, PE content and applied shear strain. This discrepancy could be explained by that the \(G^* \sin \delta\) factor did not consider the nonlinear viscoelastic behavior of asphalt binder (8). Hence, the LAS test result was more reliable, and it could be concluded that PE could improve binders’ fatigue
resistance performance. Moreover, the fatigue life increased as the PE content increased, but there was no obvious relationship between fatigue life and PE type. Appendix A shows more information and data obtained from various testing procedures employed throughout this research project.

**Conclusions**

1) Original binders

- With regards to high temperature properties, PE modifier could effectively increase the rotational viscosity, failure temperature and the $G^*/\sin \delta$ value of base binders. However, this improvement might bring side effect to the workability and compactability. And a higher PE content had greater effect on the high temperature properties. In addition, PE type had the greatest effect depended on base binder source.
- The frequency test indicated that the increased frequency generally resulted in an increase of complex modulus and a reduction of phase angle. With the increased dosage of PE, the complex modulus increased, while the phase angle values decreased in most frequencies.
- The amplitude test showed that the increased shear strain significantly reduced complex modulus and increased phase angle of binders with higher PE contents of 4% and 6% when compared to CRM and SBS binders. In terms of binder source, there was a slight change of complex modulus and phase angle for binder B with increased shear strain compared to binder A. Additional PE not only reinforced the viscosity but also enhanced the elasticity of binders.

2) RTFO-aged binders

- The PG determination, frequency sweep and amplitude sweep tests of RTFO-aged binders showed similar results to original binders.
- The MSCR test indicated the elastic performance of base binder was improved by the PE modifier, as the PE modified binders showed higher $R$ and lower $J_{nr}$ values than other references. Moreover, an increased PE content resulted in better recovery performances at high temperatures.

3) PAV-aged binders

- In terms of low temperature properties, PE modified binders showed higher critical low temperature than base binders, CRM binders and SBS binders, which meant that PE had a negative effect on low temperature property of an asphalt binder. Those binders with a higher PE content tended to have worse thermal cracking resistance.
- With respect to fatigue properties, the $G^* \sin \delta$ factor indicated that the PE modifier had a negative effect on the fatigue resistance performance, while the LAS test found that PE modified binders showed longer fatigue life, i.e. higher fatigue cracking resistance. The discrepancy might due to that the $G^* \sin \delta$ factor did not consider the nonlinear viscoelastic behavior of binder. Hence, the LAS results are hypothesized to be more reliable.
4) General Comments

- Due to limited scope of the research work, there are many other testing procedures or other various polymers or binder sources that could have been employed to make generalized comments.

- In general, laboratory binder results for this part of limited research work were satisfactory from stand point of the future utilization of these materials. However, in many cases, based on my experience, the good results obtained from lab testing do not necessarily translate to a proper hot mix asphalt (HMA) mixture.

- Based on my experience, the implementation of these materials in an actual field application and obtaining the proper acceptance from a typical DOT will not be an easy task (e.g., time wise). In many cases, specially when recycled materials are being utilized, it might take several years to be placed on the DOT’s specifications.

- The above step could be shorten by having some mix data which I am recommending to conduct for the second phase of this research work.

- It is recommended to construct a test section (e.g., 1 mile long), after obtaining lab mix data, and analyze the lab, plant, and field data before approaching any DOT officials.

- The storage stability of these binders must be investigated in more detail.

- The production (e.g., mixing process, duration of the mixing, etc.) process of these binders must be investigated in the next phase of the work.

- Various mixtures (e.g., surface, intermediate, etc.) and types (e.g., OGFC, etc.) must be investigated.

- The emulsion-base binders, made with these scrap materials, should be researched and the results reported.

- The life-cycle cost of the use of these materials must be evaluated compared to other polymer modifiers (e.g., SBS, crumb rubber, etc.).
References


Appendix A

Rotational viscosity

The viscosity values at 150 °C and 165 °C are presented in Fig. 18.

(a) Binder A at 150 °C

(b) Binder A at 165 °C
Fig. 18 Rotational viscosity results of two binder sources

$G'/\sin\delta$

The $G'/\sin\delta$ at the performance test temperatures of each binder with various PE contents and types (including original binders and RTFO-aged binders) are shown in Figs. 19 and 20.
(a) Binder A with varying PE contents (PE type: PE1)

(b) Binder A with varying PE contents (PE type: PE3)
(c) Binder A with varying PE types (PE content: 2%)

(d) Binder A with varying PE types (PE content: 6%)
(e) Binder B with varying PE contents (PE type: PE1)

(f) Binder B with varying PE contents (PE type: PE3)
(g) Binder B with varying PE types (PE content: 2%)

(h) Binder B with varying PE types (PE content: 6%)

*Fig. 19 G'/sin δ of original binders*
(a) Binder A with varying PE contents (PE type: PE1)

(b) Binder A with varying PE contents (PE type: PE3)
(c) Binder A with varying PE types (PE content: 2%)

(d) Binder A with varying PE types (PE content: 6%)
(e) Binder B with varying PE contents (PE type: PE1)

(f) Binder B with varying PE contents (PE type: PE3)
Fig. 20 $G^*/\sin \delta$ of RTFO-aged binders
Stiffness and m-value

The stiffness and m-value of each binder with various PE contents and types (including binders A and B) are shown in Fig. 21.
(c) Binder A with varying PE types (PE content: 2%)

(d) Binder A with varying PE types (PE content: 6%)
(e) Binder B with varying PE contents (PE type: PE1)

(f) Binder B with varying PE contents (PE type: PE3)
Fig. 21 Stiffness and m-value

(g) Binder B with varying PE types (PE content: 2%)

(g) Binder B with varying PE types (PE content: 6%)

52